Parameter Estimation and Analysis of Actuators for the BACT Wind-Tunnel Model

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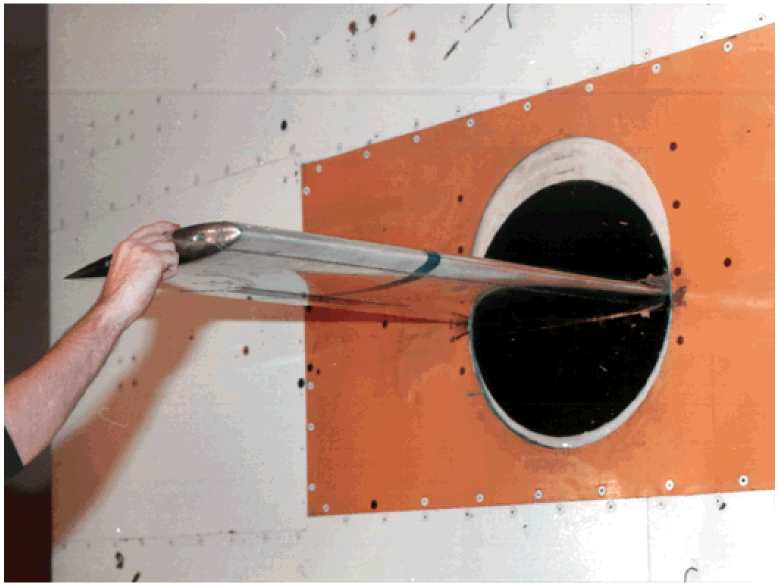
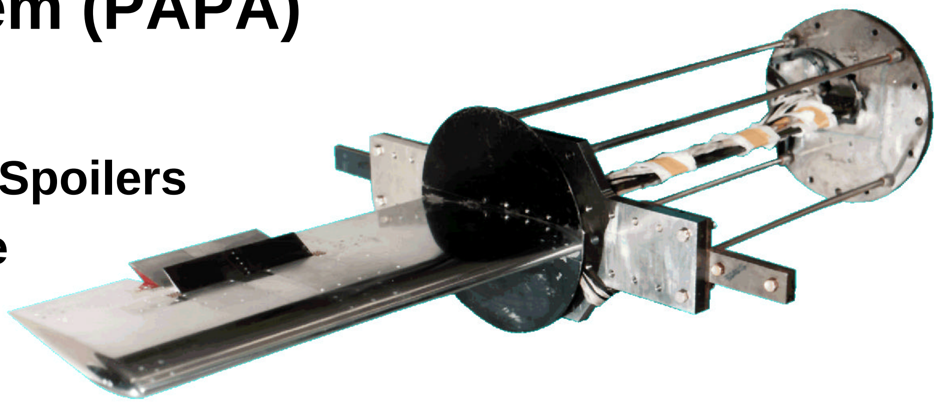


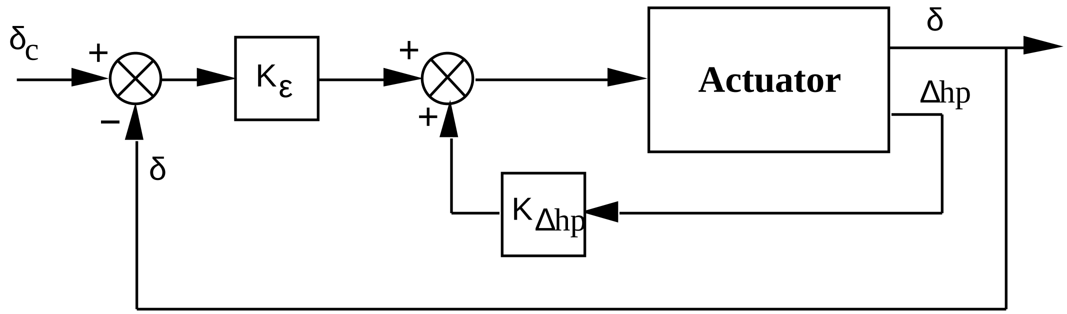
Langley Research Center
Flight Dynamic and Control Division

BACT System Overview

- **Rigid NACA 0012 Airfoil**
- **2-DOF Mounting System (PAPA)**
- **Control Surfaces**
  - **Upper and Lower Surface Spoilers**
  - **Trailing Edge Flap Surface**



- **Actuators**
  - **Hydraulic**
  - **Rotary Vane (TE) and Piston (US, LS)**
  - **Servo Loops with position and differential pressure feedback**



Objective

- **Benchmark Active Controls Technology Program**
  - **data to validate steady and unsteady aero codes**
  - **physics of aeroelastic phenomena**
  - ***active control of aeroelastic systems***
- **Models needed for active control**
  - **structural dynamics**
  - **steady and unsteady aerodynamics**
  - ***<u>actuators</u>*, sensors, controller effects**
- **Develop actuator models from experimental data**
  - **used existing data (not ideal for parameter identification)**
  - **emphasis on application to active control**

Actuator Models for Active Control

- **Modeling issues for control system design**
  - **operating condition variations and modeling uncertainties**
  - **accuracy reflected in typical control system stability margins**
    - » **Gain Margins: ± 6 dB**
    - » **Phase Margins: ± 30 degree**
  - **limited frequency range of interest**

- **Implications for actuator models**
  - **must characterize response at key frequencies**
  - **accuracy at other frequencies not critical**
  - **permit < 10% of allowable margins due to actuator modeling errors**
  - **characterize variations**
    - » **changes over time (mechanical wear and gain variations)**
    - » **hinge loading of control surfaces**

Experimental Data

- **Large data base**
  - **2300+ data points**
  - **50% involving control activity - TE:US:LS = 0.75 : 0.25 : <<1**
  - **actuator data available throughout test at variety of conditions**
    - » **early, middle, late**
    - » **unloaded and loaded**
- **Not optimized for parameter identification**
  - **high sample rate - 200 samples per second**
  - **short data runs - 25 and 75 seconds**
  - **limited frequencies of excitation - 1 to 12 Hertz**
  - **data provided in frequency response form**

Actuator Model Structure

- **3rd Order Transfer Function Model**

$$\frac{\delta(s)}{\delta_c(s)} = \frac{k\,p\,\omega^2}{(s+p)\left(s^2 + 2\zeta\,\omega\,s + \omega^2\right)}$$

- **Characterizes hydraulic systems**
  - **first order pole : flow through orifice, servo loop gain**
  - **second order poles : compressibility of fluid, control surface inertia, structural compliance, servo loop gain**
- **Compromise between objectives**
  - **simple (four parameters)**
  - **readily applicable to control system design**
  - **no nonlinearities (input amplitude dependence, dead zone, backlash, position and rate limits)**

Parameter Estimation Approach

- **Estimate four transfer function parameters :**

$$\mathbf{k}\ ,\quad \mathbf{p}\ ,\quad \omega\ ,\quad \zeta$$

- **Nonlinear Weighted Least Squares**
  - **Minimize frequency response error,** ε^2

$$\varepsilon^2 = e^T S e \qquad\qquad e = \begin{bmatrix} \Delta mag \\ \Delta phz \end{bmatrix} = \begin{bmatrix} mag_e - mag_a \\ phz_e - phz_a \end{bmatrix}$$

  - **Weighting,** ***S***

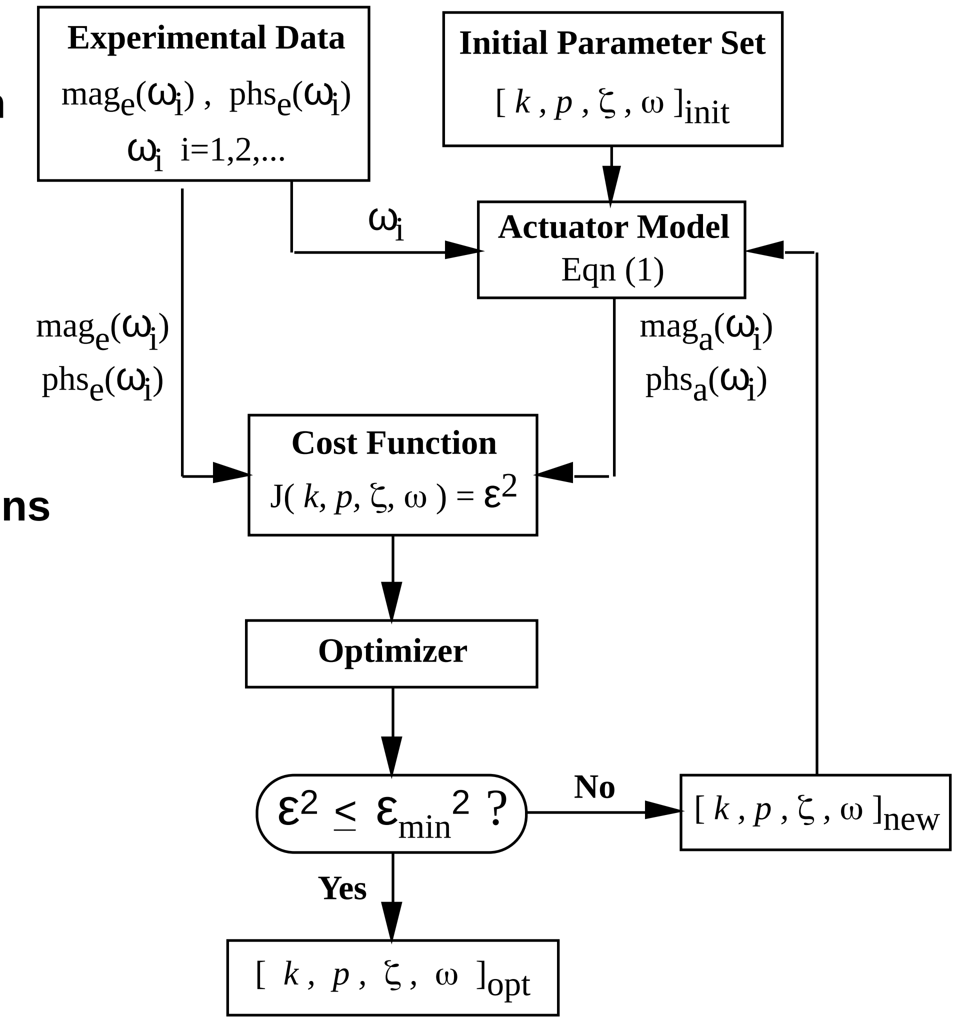
$$diag(S) = \left[c_m(\omega_1)\, c_m(\omega_2)\, c_m(\omega_3) \ldots c_m(\omega_n) \right.$$
$$\left. c_p(\omega_1)\, c_p(\omega_2)\, c_p(\omega_3) \ldots c_p(\omega_n) \right]$$

    » **emphasize frequency response magnitude or phase**

    » **emphasize selected frequencies**

Parameter Estimation Process

- **Weights : phase emphasis**
  - **phase lag key in control design**
  - **magnitude more uncertain**
- **Optimizer**
  - **quasi-newton BFGS**
  - **Matlab Optimization Toolbox**
- **Convergence Criteria**
  - **allowable error based on margins**
    - » **magnitude error < 0.1**
    - » **phase error < 3 deg**
  - **limited frequency range : 2 to 10 hertz**
  - **larger errors allowed if due to**
    - » **higher order effects**
    - » **nonlinearities**



Actuator Parameter Estimates

17 actuator models obtained encompassing

- **Trailing Edge and Upper- and Lower-Spoilers**
- **3 stages of “wear” during 3+ week test**
  - » **Early - early in week 1**
  - » **Middle - during week 2**
  - » **Late - late in week 3**
- **2 qualitative loading states**
  - » **unloaded - no aerodynamic load on actuators**
  - » **loaded - aerodynamic load at a variety of representative M and q**

Without Aero Load (M = q = 0)

Control Surface	*Test Stage*	*k (deg/deg)*	*p (1/sec)*	ω (rad/sec)	ζ
Trailing Edge Actuator	Early	1.0198	10000	165.26	0.5624
	Middle	1.0413	10000	223.57	0.7269
	Late	1.0159	10000	212.50	0.5776
Upper Spoiler Actuator	Early	1.1617	10000	164.00	0.8478
	Middle	1.1180	10000	142.02	0.6463
	Late	1.1219	10000	138.21	0.6024
Lower Spoiler Actuator	Early	1.0903	10000	168.45	0.7583
	Middle	1.0362	10000	155.08	0.6795
	Late	1.0942	10000	175.77	0.7885

With Aero Load (various M & q)

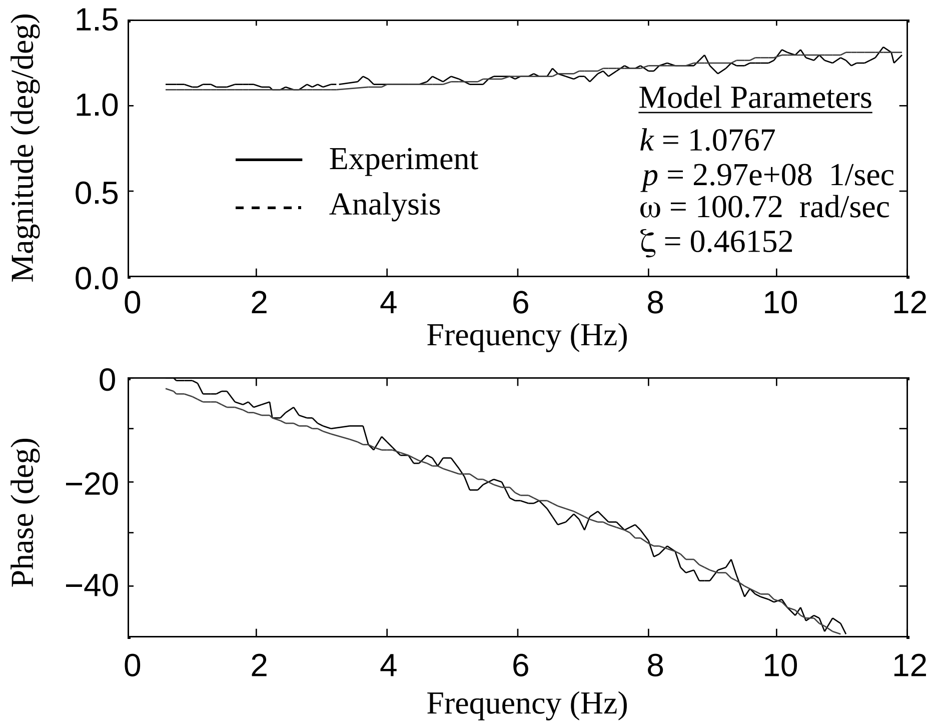
Control Surface	*Test Stage*	*k (deg/deg)*	*p (1/sec)*	ω (rad/sec)	ζ
Trailing Edge Actuator	Early	0.9607	10000	139.20	0.4281
	Middle	0.9345	10000	133.44	0.4055
	Late	1.0468	6898	242.32	0.7475
Upper Spoiler Actuator	Early	1.1152	9995	125.65	0.6187
	Middle	1.1702	9996	135.87	0.6827
	Late	1.0767	2.97e08	100.72	0.4615
Lower Spoiler Actuator	Early	1.0289	9998	145.07	0.6314
	Middle	1.0265	9999	150.85	0.6444
	Late	N/A	N/A	N/A	N/A

Actuator Model Accuracy

Frequency Response Error

– **errors within 10% of typical margins**

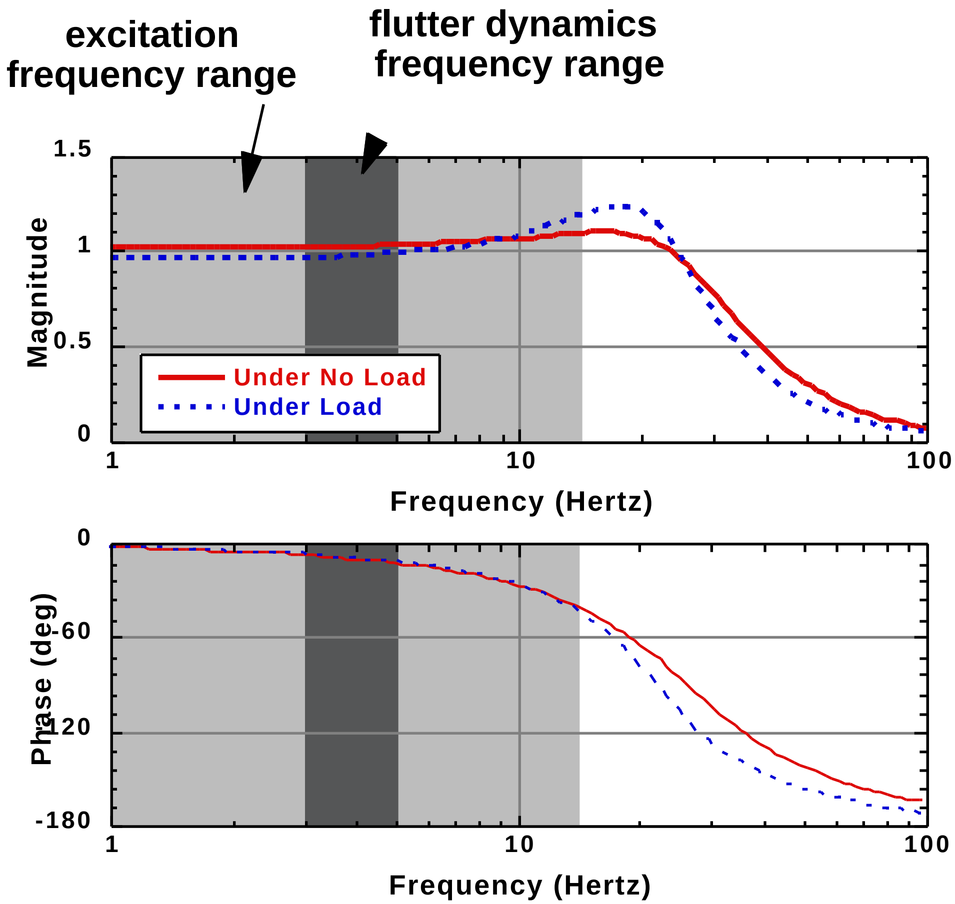
– **only applies over frequency range of experimental data**



Upper Spoiler with Aero Load (M=0.8, q 140 psf), Late

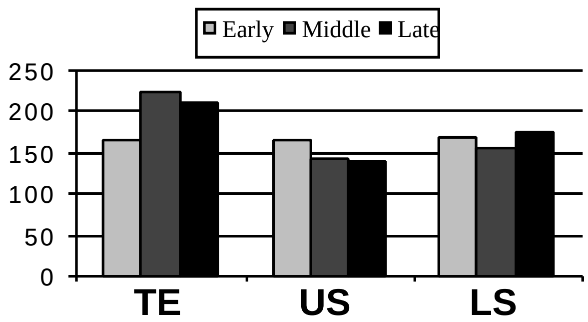
Parameter Accuracy

Available data only describes part of the frequency range over which parameters have influence

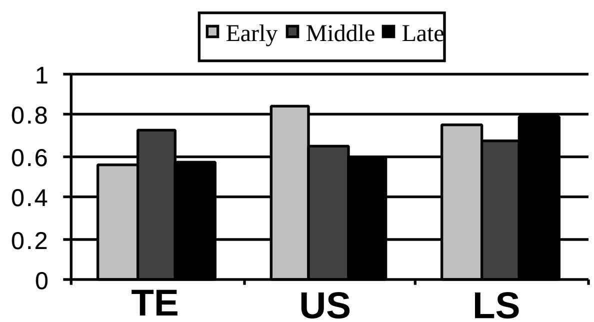


Analysis of Variations Over Time

- **Variations due to**
  - **mechanical wear**
  - **servo gain variations**

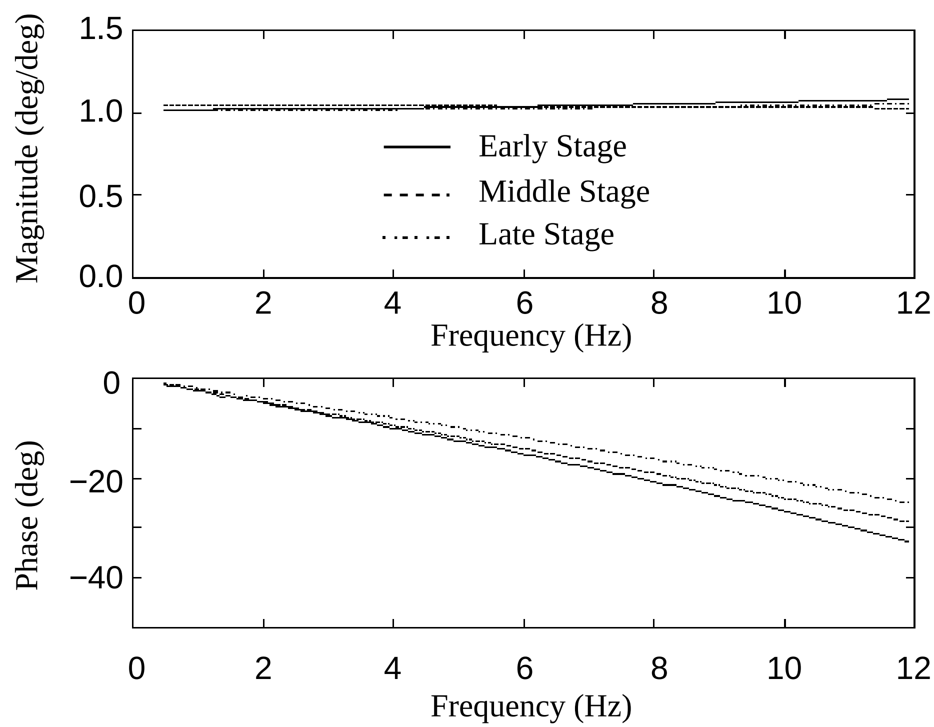


Frequency Parameter, ω



Damping Parameter, ζ

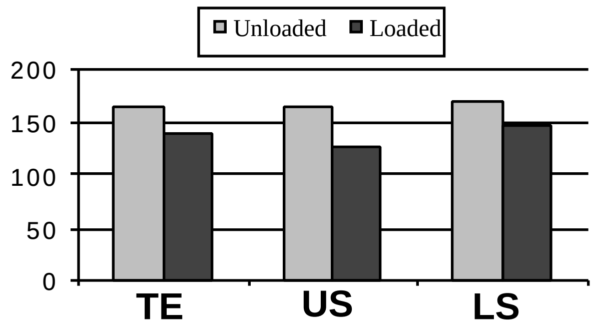
Trailing Edge Control Frequency Response - No Load



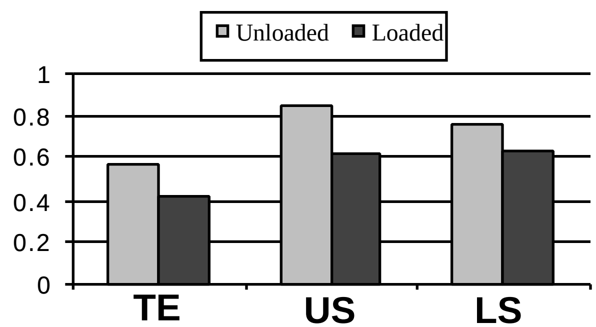
- **small magnitude effects**
- **significant phase effects past 6 Hz**

Analysis of Variations due to Loading

- **Aero loading effects**
  - **qualitative (various M & q)**
  - **isolated from other effects early in test**

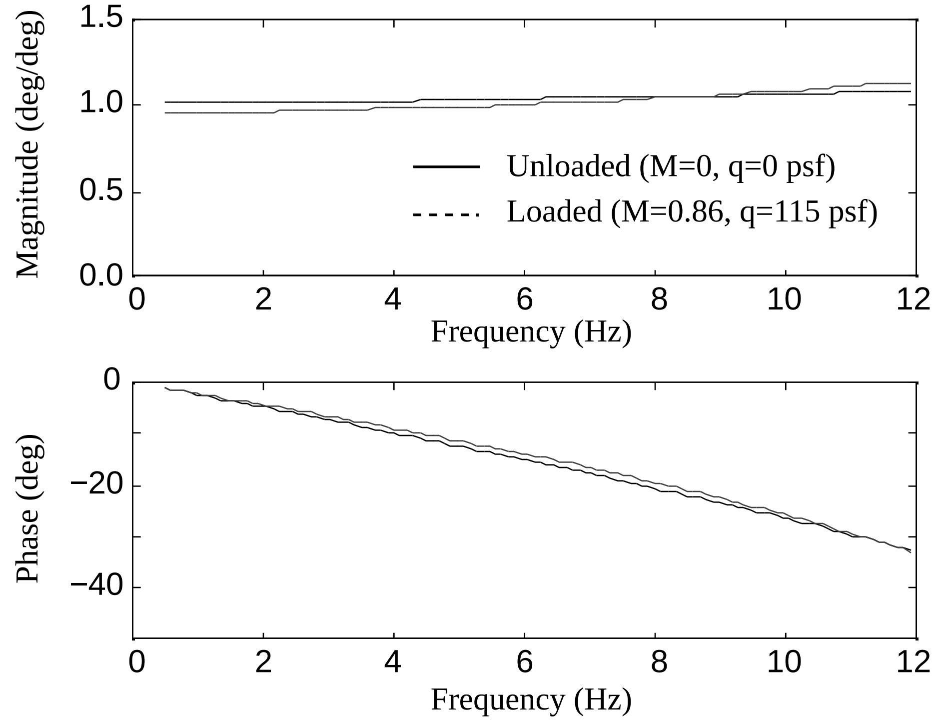


Frequency Parameter, ω



Damping Parameter, ζ

Trailing Edge Control Frequency Response - Early



- **magnitude and phase variations < 10% of typical margins**
- **variations due to load not an issue**

Analysis of Model Order Issue

Potential overparameterization of model

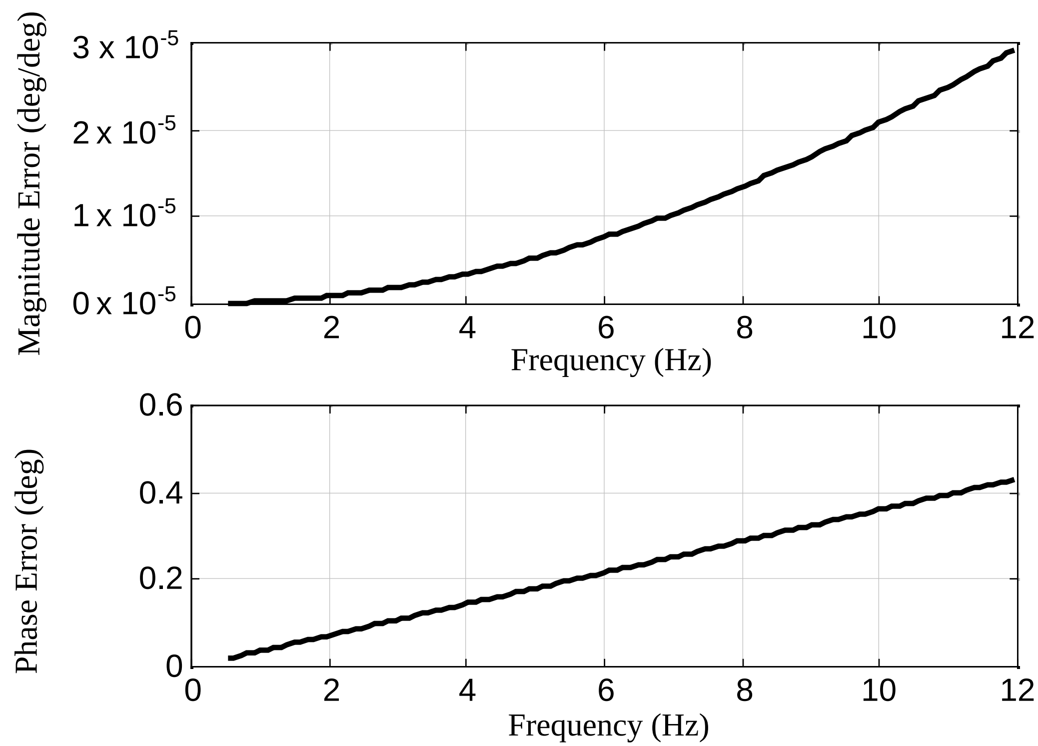
- insensitive to first order pole location
- eliminate p from model

$$\frac{p}{s+p} \quad 1 \quad for\ s << p$$

$$\frac{k\,p\,\omega^2}{(s+p)\left(s^2 + 2\zeta\,\omega\,s + \omega^2\right)}$$

vs.

$$\frac{k\,\omega^2}{\left(s^2 + 2\zeta\,\omega\,s + \omega^2\right)}$$



Error Between 3rd and 2nd Order Model

Concluding Remarks

- **Parameter Estimation**
  - **estimated parameters of 3rd order transfer function model accurately characterize frequency response data**
  - **parameter accuracy not specifically addressed**
- **Applications**
  - **suitable for control system design applications**
  - **average model probably acceptable in most instances**
  - **estimated parameters can be used to represent model variation or uncertainty**
  - **2nd order actuator model form can be used**
- **Included in simulation model of BACT system**
- **Have been applied in several control system designs and successfully tested**